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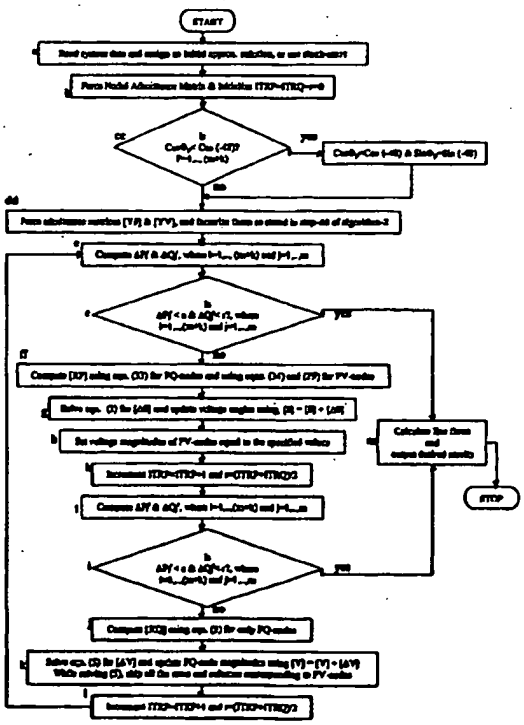
(54) Title: SYSTEM OF SUPER SUPER DECOUPLED LOADFLOW COMPUTATION FOR ELECTRICAL POWER SYSTEM



Flow-chart of SSDL-YY solution algorithm-2

(57) Abstract: Load-Flow computations are performed in real-time operation/control and in on-line/off-line studies of electrical power systems. Three Load-Flow computation methods of the present invention are the best versions of many simple variants with almost similar performance. The Super Super Decoupled Loadflow (SSDL-YY) method and its many variants are characterized in limiting rotation angle applied to nodal real and reactive power mismatches to the maximum of -48 degrees instead of -36 degrees, replacing network shunt element $-2b_pCos\Phi_p$ by $[2(QSH_pCos\Phi_p - PSH_pSin\Phi_p)/V_s^2]$ or by $[-b_pCos\Phi_p + (QSH_pCos\Phi_p - PSH_pSin\Phi_p)/V_s^2]$ and using the dividing term V^2 instead of V in the modified nodal real power residues [RP] in the prior art Fast Super Decoupled Loadflow (FSDL) method. The other two Super Super Decoupled Loadflow: BGX' version (SSDL-BGX') and $X'G_{pv}X'$ version (SSDL-$X'G_{pv}X'$) are characterized in the use of simultaneous (1V,1θ) iteration scheme thereby reducing the mismatch computation once compared to two mismatch computations in the prior art method employing successive (1θ,1V) iteration scheme. The invented methods are also characterized in the different definition of gain matrices as detailed in the steps of algorithm-2, algorithm-3 and algorithm-4 of carrying out of the inventions. (steps-cc, -dd, and ff in Fig.2; steps-ccc, -ddd, -fff, -ggg and -hhh in Fig.3; steps-dddd and -ffff in Fig. 4) leading to some speed-up of the invented methods.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

SYSTEM OF SUPER SUPER DECOUPLED LOADFLOW COMPUTATION FOR ELECTRICAL POWER SYSTEM

TECHNICAL FIELD

The present invention relates to methods of loadflow computation in power flow control and voltage control for an electrical power system.

BACKGROUND ART AND MOTIVATION

Utility/industrial power networks are composed of many power plants/generators interconnected through transmission/distribution lines to other loads and motors. Each of these components of the power network is protected against unhealthy (faulty, over/under voltage, over loaded) potentially damaging operating conditions. Such protection is automatic and operates without the consent of power network operator, and takes an unhealthy component out of service disconnecting it from the network. The time domain of operation of the protection is of the order of milliseconds.

The purpose of a utility/industrial power network is to meet the electricity demands of its various consumers 24-hours a day, 7-days a week while maintaining the quality of electricity supply. The quality of electricity supply means the consumer demands be met at specified (say + or - 5% tolerance) voltage and frequency levels without over loaded, under/over voltage operation of any of the power network components. The operation of a power network is different at different times due to changing consumer demands and/or development of any faulty/contingency situation. In other words healthy operating power network is constantly subjected to small or large disturbances. These disturbances could be operator initiated, or initiated by security control functions and various optimization functions such as economic operation, minimization of losses etc., or caused by a fault/contingency incident.

For example, a power network is operating healthy and meeting quality electricity needs of its consumers. A fault occurs on a line or a transformer or a generator which faulty component gets isolated from the rest of the healthy network by virtue of the automatic operation of its protection. Such a disturbance would cause a change in the pattern of power flows in the network, which can cause over loading of one or more of the other components and/or over/under voltage at one or more nodes in the rest of the network. This in turn can isolate one or more other components out of service by virtue of the operation of associated protection, which disturbance can trigger chain reaction disintegrating the power network.

Therefore, the most basic and integral part of all other functions (e.g. optimizations) in power network operation and control is security control. Security control means controlling power flows so that no component of the network is over loaded and controlling voltages such that there is no over voltage or under voltage at any of the nodes in the network following a disturbance small or large. Security control functions (overload alleviation and over/under voltage alleviation) can be realized through one or combination of more controls in the network. These involve control of power flow over tie line connecting other utility network, turbine steam/water input control to control real power generated by each generator, load shedding function curtails load demands of consumers, excitation controls reactive power generated by individual generator which essentially controls generator terminal voltage, transformer taps control connected node voltage, switching in/out in capacitor/reactor banks controls reactive power at the connected node. Such overload and under/over voltage alleviation functions produce control amount changes in step-60 of Fig.5. These control amount changes could be even optimized in case of simulation of all possible imaginable disturbances (outage of a line, loss of generation etc.) for corrective action stored and made readily available for acting upon in case the simulated disturbance actually occurs in the power network. In fact simulation of all possible imaginable disturbances is the modern practice because corrective actions need be taken before the operation of individual protection of unhealthy component.

Control of an electrical power system (Power-flow control, voltage control etc.) is performed according to the process flow diagram of fig.5. The various numbered steps in fig.5 are explained in the following.

Step-10: On-line readings of various real-time power flows, voltages, circuit breaker status (open/close) etc. are obtained

Step-20: A control amount (i.e. change in power injections, voltages etc.) is initially established and proposed

Step-30: Various power flows, voltage magnitudes and angles, reactive power generations by generators and turns ratios of transformers in the power system are determined by performing loadflow computation, which incorporates established/proposed/set control adjustments

Step-40: The results of Loadflow computation of step 30 are evaluated for any over loaded transmission lines and over/under voltages at different nodes in the power system

Step-50: If the system state is good (no over loaded lines and no over/under voltages), the process branches to step 70, otherwise to 60

Step-60: Changes the control amount initially set in step-20 or later set in the previous process cycle step-60 and returns to step-30

Step-70: Actually implements the control amount correction to obtain secure/optimum/correct/acceptable operation of power system

It is obvious that Loadflow computation is performed many times in real-time operation and control environment and, therefore, **high-speed (efficient) Loadflow computation is necessary** to provide corrective control in the changing power system conditions including an outage or failure. Moreover, the **loadflow computations must be highly reliable to yield converged solution under wide range of system operating conditions and network parameters**. Failure to yield converged loaflow solution creates blind spot as to what exactly could be happening in the network leading to potentially damaging operational and control decisions/actions in capital-intensive power utilities.

The embodiment of the present invention, the most efficient and reliable loadflow computations, as described in the above steps and in Fig.5 is very general and elaborate. The control of voltage magnitude within reactive power generation capabilities of electrical machines (generators, synchronous motors, capacitor/inductor banks) and within operating ranges of transformer taps is normally integral part of Loadflow computation as described in "LTC Transformers and MVAR violations in the Fast Decoupled Loadflow, IEEE PAS-101, No.9, PP. 3328-3332." If under/over voltage still exists in the results of Loadflow computations, other control actions are taken in step-60 in the above and in Fig.5. For example, under voltage can be alleviated by shedding some of the load connected.

However, the simplest embodiment of the efficient and reliable system and method of loadflow computations is where only voltage magnitudes are controlled by controlling reactive power generation of generators and motors, switching in/out in capacitor/inductor banks and transformer taps. Of course, such control is possible only within reactive power capabilities of machines and capacitor/reactor banks, and within operating ranges of transformer taps. This is the case of a network in which the real power assignments have already been fixed and in which steps-50 and -60 in the above and in Fig.5 are absent. Once loadflow computations are finished, the Loadflow solution includes indications of reactive power generation at generator nodes and at the nodes of the capacitor/inductor banks, and indications of transformer tap settings. Based on the known reactive power capability characteristics of the individual machines, the determined reactive power values are used to adjust the excitation current to each machine, or at least each machine presently under reactive power, or VAR, control, to establish the desired reactive power set points. The transformer taps are set in accordance with the tap setting indications produced by the Loadflow computation system.

This procedure can be employed either on-line or off-line. In off-line operation, the user can simulate and experiment with various sets of operating conditions and determine reactive power generation and transformer tap settings requirements. A general-purpose computer can implement the entire system. For on-line operation, the loadflow computation system is provided with data identifying the current real and reactive power assignments

and transformer transformation ratios, the present status of all switches and circuit breakers in the network and machine characteristic curves in steps-10 and -20 in the above and in Fig. 5, and blocks 10, 12, 14, 20, 30, 40, 42, 44, 50, 52 in Fig 6. Based on this information, a model of the system based on gain matrices of any of the invented or prior art Loadflow computation methods provide the values for the corresponding node voltages, reactive power set points for each machine and the transformation ratio and tap changer position for each transformer.

The present invention relates to control of utility/industrial power networks of the types including plurality of power plants/generators and one or more motors/loads, and connected to other external utility. In the utility/industrial systems of this type it is the usual practice to adjust the real and reactive power produced by each generator and each of the other sources (synchronous condensers, capacitor/inductor banks) in order to optimize the real and reactive power generation assignments of the system. Healthy (secure) operation of the network can be shifted to optimized operation through corrective control (disturbance) produced by optimization functions without violation of security constraints. This is referred to as security constrained optimization of operation. Such an optimization is described in the United States Patent Number: 5,081,591 dated Jan. 13, 1992 (Optimizing Reactive Power Distribution in an Industrial Power Network) where the present invention can be embodied by replacing the block nos. 56 and 66 by a block of constant matrices [Yθ] and [YV], and replacing blocks of "Exercise Newton-Raphson Algorithm" by blocks of "Exercise Fast Super Decoupled Algorithm" or "Execise Super Super Decoupled Algorithm" in place of blocks 58 and 68.

DISCLOSURE OF THE INVENTION

This invention relates to steady-state power network computation referred to as Loadflow or Power-Flow. Loadflow computations are performed as a step in real-time operation/control and in on-line/off-line studies of Electrical Power Systems. The present invention involves three-methods. These 3-methods are the best versions of many simple variants with almost similar performance. Simple variants include any possible hybrid

combination of these 3-methods and unsymmetrical definitions of [Yθ] in SSDL-method. **Among these 3-methods, their variants and all other known methods, Super Super Decoupled Loadflow (SSDL-YY) is the simplest, easiest to implement and overall best in performance (reliability of convergence and efficiency of computations).**

BRIEF DESCRIPTION OF DRAWINGS

Fig. 1 is a flow-chart of the prior art Fast Super Decoupled Loadflow computation method

Fig. 2 is a flow-chart embodiment of the invented Super Super Decoupled Loadflow computation method of version SSDL-YY

Fig. 3 is a flow-chart embodiment of the invented Super Super Decoupled Loadflow: SSDL-BGX', -BGY, and -BGX versions

Fig. 4 is a flow-chart embodiment of the invented Super Super Decoupled Loadflow: SSDL-X'G_{pv}X', SSDL-YG_{pv}Y, and SSDL- XG_{pv}X versions

Fig. 5 is a flow-chart of the overall controlling method for an electrical power system involving Loadflow computation as a step which can be executed using one of the Loadflow computation methods of Figs. 1, 2, 3, 4, other variations described, their hybrid combination and/or their simple variants

Fig. 6 is a flow-chart of the simple special case of voltage control in overall controlling method of Fig. 5 for an electrical power system

Symbols

The prior art and inventions will now be described using the following symbols:

$\overline{Y}_{pq} = G_{pq} + jB_{pq}$: (p-q) th element of nodal admittance matrix without shunts

$\overline{y} = g_p + jb_p$: total shunt admittance at any node-p

$\overline{V}_p = e_p + jf_p = V_p\angle\theta_p$: complex voltage of any node-p

$\overline{V}_s = e_s + jf_s = V_s\angle\theta_s$: complex slack-node voltage

$\Delta\theta_p$, ΔV_p : voltage angle, magnitude corrections

Δe_p, Δf_p : real, imaginary components of voltage corrections

$P_p + jQ_p$	: net nodal injected power, calculated
$\Delta P_p + j\Delta Q_p$	: nodal power residue (mismatch)
$RP_p + jRQ_p$	: modified nodal power residue
$PSH_p + jQSH_p$	: net nodal injected power, scheduled
Φ_p	: rotation angle
m	: number of PQ-nodes
k	: number of PV-nodes
n=m+k+1	: total number of nodes
q>p	: q is the node adjacent to node-p excluding the case of q=p
[ ]	: indicates enclosed variable symbol to be a vector or a matrix
LRA	: Limiting Rotation Angle
PQ-node	: load-node (Real-Power-P and Reactive-Power-Q are specified)
PV-node	: generator-node (Real-Power-P and Voltage-Magnitude-V are specified)

Decoupled Loadflow

A class of decoupled Loadflow methods involves a system of equations for the separate calculation of voltage angle and voltage magnitude corrections. Each decoupled method comprises a system of equations (1) and (2) differing in the definition of elements of [RP], [RQ], and [Yθ] and [YV].

$$[RP] = [Y\theta]\,[\Delta\theta] \quad (1)$$

$$[RQ] = [YV]\,[\Delta V] \quad (2)$$

Successive (1θ, 1V) Iteration Scheme

In this scheme (1) and (2) are solved alternately with intermediate updating. Each iteration involves one calculation of [RP] and [Δθ] to update [θ] and then one calculation of [RQ] and [ΔV] to update [V]. The sequence of relations (3) to (6) depicts the scheme.

$$[\Delta\theta] = [Y\theta]^{-1} [RP] \quad (3)$$

$$[\theta] = [\theta] + [\Delta\theta] \quad (4)$$

$$[\Delta V] = [YV]^{-1} [RQ] \quad (5)$$

$$[V] = [V] + [\Delta V] \quad (6)$$

The scheme involves solution of system of equations (1) and (2) in an iterative manner depicted in the sequence of relations (3) to (6). This scheme requires mismatch calculation for each half iteration; because [RP] and [RQ] are calculated always using the most recent voltage values and it is block Gauss-Seidal approach. The scheme is block successive, which imparts increased stability to the solution process. This in turn improves convergence and increases the reliability of obtaining solution.

PRIOR ART: FAST SUPER DECOUPLED LOADFLOW METHO
(References-3, 6, 7)

Fast Super Decoupled Loadflow (FSDL) Method

$$RP_p = (\Delta P_p \text{Cos}\Phi_p + \Delta Q_p \text{Sin}\Phi_p)/V_p \quad \text{-for PQ-nodes} \quad (7)$$

$$RQ_p = (\Delta Q_p \text{Cos}\Phi_p - \Delta P_p \text{Sin}\Phi_p)/V_p \quad \text{-for PQ-nodes} \quad (8)$$

$$\text{Cos}\Phi_p = \text{Absolute}\,(B_{pp} / \sqrt{(G_{pp}^2 + B_{pp}^2)}) \geq \text{Cos}\,(-36°) \quad (9)$$

$$\text{Sin}\Phi_p = -\text{Absolute}\,(G_{pp} / \sqrt{(G_{pp}^2 + B_{pp}^2)}) \geq \text{Sin}\,(-36°) \quad (10)$$

$$RP_p = \Delta P_p / (K_p V_p) \quad \text{-for PV-nodes} \quad (11)$$

$$Y\theta_{pq} = \begin{cases} -Y_{pq} & \text{-for branch r/x ratio} \le 2.0 \\ -(B_{pq} + 0.9(Y_{pq}-B_{pq})) & \text{-for branch r/x ratio} > 2.0 \\ -B_{pq} & \text{-for branches connected between two PV-nodes or a PV-node and the slack-node} \end{cases} \quad (12)$$

$$YV_{pq} = \begin{cases} -Y_{pq} & \text{-for branch r/x ratio} \le 2.0 \\ -(B_{pq} + 0.9(Y_{pq}-B_{pq})) & \text{-for branch r/x ratio} > 2.0 \end{cases} \quad (13)$$

$$Y\theta_{pp} = \sum_{q \neq p} -Y\theta_{pq} \quad \text{and} \quad YV_{pp} = -2b_p' + \sum_{q \neq p} -YV_{pq} \quad (14)$$

$$b_p' = b_p \mathrm{Cos}\Phi_p \quad \text{or} \quad b_p' = b_p \quad (15)$$

$$K_p = \text{Absolute}\,(B_{pp}/Y\theta_{pp}) \quad (16)$$

Branch admittance magnitude in (12) and (13) is of the same algebraic sign as its susceptance. Elements of the two gain matrices differ in that diagonal elements of [YV] additionally contain the b' values given by relation (15) and in respect of elements corresponding to branches connected between two PV-nodes or a PV-node and the slack-node. Relations (9) and (10) with inequality sign implies that nodal rotation angles are restricted to maximum of -36 degrees. The method consists of relations (3) to (16). In two simple variations of the FSDL method, one is to make $YV_{pq}=Y\theta_{pq}$ and the other is to make $Y\theta_{pq}=YV_{pq}$. K_p is restricted to the minimum value of 0.75 determined experimentally, and it is system independent. However it can be tuned for the best possible convergence for any given system.

This prior art method involves solution of system of equations (1) and (2) in an iterative manner depicted in sequence of relations (3) to (6). Prior art method is embodied in algorithm-1, and in the flow-chart of fig.1.

Computation steps of FSDL method (Algorithm-1):

a. Read system data and assign an initial approximate solution. If better solution estimate is not available, set voltage magnitude and angle of all nodes equal to those of the slack-node. This is referred to as the **slack-start.**

b. Form nodal admittance matrix, and Initialize iteration count ITRP = ITRQ= r = 0

c. Compute Cosine and Sine of nodal rotation angles using relations (9) and (10), and store them. If they, respectively, are less than the Cosine and Sine of -36 degrees, equate them, respectively, to those of -36 degrees.

d. Form (m+k) x (m+k) size matrices [Yθ] and [YV] of (1) and (2) respectively each in a compact storage exploiting sparsity. The matrices are formed using relations (12), (13), (14), and (15). In [YV] matrix, replace diagonal elements corresponding to PV-nodes by very large value (say, 10.0**10). In case [YV] is of dimension (m x m), this is not required to be performed. Factorize [Yθ] and [YV] using the same ordering of nodes regardless of node-types and **store them using the same indexing and addressing information.** In case [YV] is of dimension (m x m), it is factorized using different ordering than that of [Yθ].

e. Compute residues [ΔP] (PQ- and PV-nodes) and [ΔQ] (at only PQ-nodes). If all are less than the tolerance (ε), proceed to step (m). Otherwise follow the next step.

f. Compute the vector of modified residues [RP] using (7) for PQ-nodes, and using (11) and (16) for PV-nodes.

g. Solve (3) for [Δθ] and update voltage angles using, [θ] = [θ] + [Δθ].

h. Set voltage magnitudes of PV-nodes equal to the specified values, and Increment the iteration count ITRP=ITRP+1 and r=(ITRP+ITRQ)/2.

i. Compute residues [ΔP] (PQ- and PV-nodes) and [ΔQ] (at PQ-nodes only). If all are less than the tolerance (ε), proceed to step (m). Otherwise follow the next step.

j. Compute the vector of modified residues [RQ] using (8) for only PQ-nodes.

k. Solve (5) for [ΔV] and update PQ-node magnitudes using [V] = [V] + [ΔV]. While solving equation (5), skip all the rows and columns corresponding to PV-nodes.

l. Increment the iteration count ITRQ=ITRQ+1 and r=(ITRP+ITRQ)/2, and Proceed to step (e)

m. Calculate line flows and output the desired results

INVENTED SUPER SUPER DECOUPLED LOADFLOW METHODS

Super Super Decoupled Loadflow: X'X'-version (SSDL-X'X')

The general method, in successive (1θ, 1V) iteration scheme represented by sequence of relations (3) to (6), can be realized as SSDL-X'X', from which manifested are many versions. The elements of [RP], [RQ], [Yθ] and [YV] are defined by (17) to (29).

$$RP_p = [\Delta P_p' + (G_{pp}'/B_{pp}')\,\Delta Q_p'] / V_p^2 \qquad \text{-for PQ-nodes} \qquad (17)$$

$$RQ_p = [\Delta Q_p' - (G_{pp}'/B_{pp}')\,\Delta P_p'] / V_p \qquad \text{-for PQ-nodes} \qquad (18)$$

$$RP_p = [\Delta P_p / (K_p * V_p^2)] \qquad \text{-for PV-nodes} \qquad (19)$$

$$Y\theta_{pq} = -1/X_{pq}' \quad \text{and} \quad YV_{pq} = -1/X_{pq}' \qquad (20)$$

$$Y\theta_{pp} = \sum_{q>p} -Y\theta_{pq} \quad \text{and} \quad YV_{pp} = b_p' + \sum_{q>p} -YV_{pq} \qquad (21)$$

Where,

$b_p' = -2b_p \mathrm{Cos}\Phi_p$ or

$b_p' = -b_p \mathrm{Cos}\Phi_p + [QSH_p' - (G_{pp}'/B_{pp}')\,PSH_p'] / V_s^2$ or

$b_p' = 2[QSH_p' - (G_{pp}'/B_{pp}')\,PSH_p'] / V_s^2 \qquad (22)$

$$\Delta P_p' = \Delta P_p \mathrm{Cos}\Phi_p + \Delta Q_p \mathrm{Sin}\Phi_p \qquad \text{-for PQ-nodes} \qquad (23)$$

$$\Delta Q_p' = \Delta Q_p \mathrm{Cos}\Phi_p - \Delta P_p \mathrm{Sin}\Phi_p \qquad \text{-for PQ-nodes} \qquad (24)$$

$$PSH_p' = PSH_pCos\Phi_p + QSH_pSin\Phi_p \quad \text{-for PQ-nodes} \quad (25)$$

$$QSH_p' = QSH_pCos\Phi_p - PSH_pSin\Phi_p \quad \text{-for PQ-nodes} \quad (26)$$

$$Cos\Phi_p = \text{Absolute } [B_{pp} / v\,(G_{pp}^2 + B_{pp}^2)] \geq \text{Cos (any angle from 0 to -90 degrees)} \quad (27)$$

$$Sin\Phi_p = \text{-Absolute } [G_{pp} / v\,(G_{pp}^2 + B_{pp}^2)] \geq \text{Sin (any angle from 0 to -90 degrees)} \quad (28)$$

$$K_p = \text{Absolute } (B_{pp}/Y\theta_{pp}) \quad (29)$$

The factor K_p of (29) is initially restricted to the minimum of 0.75 determined experimentally; however its restriction is lowered to the minimum value of 0.6 when its average over all PV-nodes is less than 0.6. This factor is system and method independent. However it can be tuned for the best possible convergence for any given system. This statement is valid when the factor K_p is applied in the manner of equation (19) in all the methods derived in the following from the most general method SSDL-X'X'.

The definition of $Y\theta_{pq}$ in (20) is simplified because it does not explicitly state that it always takes the value of $-B_{pq}$ for a branch connected between two PV-nodes or a PV-node and the slack-node. This fact should be understood implied in all the definitions of $Y\theta_{pq}$ in this document.

However, a whole new class of methods, corresponding to all those derived in the following and prior art, results when the factor K_p is used as a multiplier in the definition of RP_p at PQ-nodes as in (30) instead of divider in RP_p at PV-nodes as given in (19). This will cause changes only in relations (17), (19), and (20) as given in (30), (31), and (32).

$$RP_p = \{[\Delta P_p' + (G_{pp}' / B_{pp}')\,\Delta Q_p']\,/\,V_p^2\} * K_p \quad \text{-for PQ-nodes} \quad (30)$$

$$RP_p = \Delta P_p / V_p^2 \quad \text{-for PV-nodes} \quad (31)$$

$$Y\theta_{pq} = -B_{pq} \quad \text{and} \quad YV_{pq} = -1/X_{pq}' \tag{32}$$

The best performance of methods of this new class has been realized when the factor K_p, applied in a manner of relation (30) leading to changes as in (30) to (32), is unrestricted. That means it can take any value as given by relation (29).

Super Super Decoupled Loadflow: YY-version (SSDL-YY)

If unrestricted rotation is applied and transformed susceptance is taken as admittance value with the same algebraic sign and transformed conductance is assumed zero (reference-6), the SSDL-X'X' method reduces to SSDL-YY. Though, this method is not very sensitive to the restriction applied to nodal rotation angles, SSDL-YY presented here is the best possible experimentally arrived at method. However, it gives closely similar performance over wide range of restriction applied to the nodal rotation angles (say from -36 to -90 degrees).

$$RP_p = \Delta P_p'/ V_p^2 \quad \text{and} \quad RQ_p = \Delta Q_p'/ V_p \quad \text{-for PQ-nodes} \tag{33}$$

$$RP_p = \Delta P_p / (K_p V_p^2) \quad \text{-for PV-nodes} \tag{34}$$

$$Y\theta_{pq} = \begin{cases} -Y_{pq} & \text{-for branch r/x ratio} \le 3.0 \\ -(B_{pq} + 0.9(Y_{pq}-B_{pq})) & \text{-for branch r/x ratio} > 3.0 \\ -B_{pq} & \text{-for branches connected between two PV-nodes or a PV-node and the slack-node} \end{cases} \tag{35}$$

$$YV_{pq} = \begin{cases} -Y_{pq} & \text{-for branch r/x ratio} \le 3.0 \\ -(B_{pq} + 0.9(Y_{pq}-B_{pq})) & \text{-for branch r/x ratio} > 3.0 \end{cases} \tag{36}$$

$$Y\theta_{pp} = \sum_{q>p} -Y\theta_{pq} \quad \text{and} \quad YV_{pp} = b_p' + \sum_{q>p} -YV_{pq} \tag{37}$$

$$b_p' = (QSH_p'/ V_s^2) - b_p \text{Cos}\Phi_p \quad \text{or} \quad b_p' = 2QSH_p'/ V_s^2 \tag{38}$$

where, $\Delta P_p'$, $\Delta Q_p'$, QSH_p' , and K_p are defined in relations (23) to (29). However, nodal rotation angles in relations (27) and (28) be **restricted to the maximum of -48 degrees for this method,** determined experimentally for the best possible convergence from non linearity considerations.

In case of systems of only PQ-nodes and without any PV-nodes, equations (35) and (36) simply be taken as $Y\theta_{pq} = -Y_{pq}$ and $YV_{pq} = -Y_{pq}$. The factor K_p of (29) is initially restricted to the minimum of 0.75 determined experimentally; however its restriction is lowered to the minimum value of 0.6 when its average over all PV nodes is less than 0.6. This factor is system independent. However it can be tuned for the best possible convergence for any given system.

Branch admittance magnitude in (35) and (36) is of the same algebraic sign as its susceptance. Elements of the two gain matrices differ in that diagonal elements of [YV] additionally contain the b' values given by relations (37) and (38) and in respect of elements corresponding to branches connected between two PV-nodes or a PV-node and the slack-node. Relations (27) and (28) with inequality sign implies that nodal rotation angles are restricted to maximum of -48 degrees for SSDL-YY. The method consists of relation's (3) to (6), (33) to (38), and (23) to (29). In two simple variations of the SSDL-YY method, one is to make $YV_{pq}=Y\theta_{pq}$ and the other is to make $Y\theta_{pq}=YV_{pq}$.

SSDL-YY method implements successive (1θ, 1V) iteration scheme and is embodied in algorithm-2, and in flow-chart of fig.2 where double lettered steps are characteristic steps of the SSDL-YY method and are different than those of the prior art FSDL method.

Computation steps of SSDL-YY method (Algorithm-2):

a. Read system data and assign an initial approximate solution. If better solution estimate is not available, set voltage magnitude and angle of all nodes equal to those of the slack-node. This is referred to as the **slack-start.**

b. Form nodal admittance matrix, and Initialize iteration count ITRP = ITRQ= r = 0

cc. Compute Cosine and Sine of nodal rotation angles using relations (27) and (28), and store them. If they, respectively, are less than the Cosine and Sine of -48 degrees, equate them, respectively, to those of -48 degrees.

dd. Form (m+k) x (m+k) size matrices [Yθ] and [YV] of (1) and (2) respectively each in a compact storage exploiting sparsity. The matrices are formed using relations (35), (36), (37), and (38). In [YV] matrix, replace diagonal elements corresponding to PV-nodes by very large value (say, 10.0**10). In case [YV] is of dimension (m x m), this is not required to be performed. Factorize [Yθ] and [YV] using the same ordering of nodes regardless of node-types and **store them using the same indexing and addressing information.** In case [YV] is of dimension (m x m), it is factorized using different ordering than that of [Yθ].

e. Compute residues ΔP (PQ- and PV-nodes) and ΔQ (at only PQ-nodes). If all are less than the tolerance (ε), proceed to step (m). Otherwise follow the next step.

ff. Compute the vector of modified residues [RP] as in (33) for PQ-nodes, and using (34) and (29) for PV-nodes.

g. Solve (3) for [Δθ] and update voltage angles using, [θ] = [θ] + [Δθ].

h. Set voltage magnitudes of PV-nodes equal to the specified values, and Increment the iteration count ITRP=ITRP+1 and r=(ITRP+ITRQ)/2.

i. Compute residues [ΔP] (PQ- and PV-nodes) and [ΔQ] (at PQ-nodes only). If all are less than the tolerance (ε), proceed to step (m). Otherwise follow the next step.

j. Compute the vector of modified residues [RQ] as in (33) for only PQ-nodes.

k. Solve (5) for [ΔV] and update PQ-node magnitudes using [V] = [V] + [ΔV]. While solving equation (5), skip all the rows and columns corresponding to PV-nodes.

l. Increment the iteration count ITRQ=ITRQ+1 and r=(ITRP+ITRQ)/2, and Proceed to step (e)

m. Calculate line flows and output the desired results

Super Super Decoupled Loadflow: XX-version (SSDL-XX)

If no (zero) rotation is applied, the SSDL-X'X' method reduces to SSDL-XX, which is the simplest form of SSDL-X'X'. The SSDL-XX method comprises relations (3) to (6), (39) to (45), and (29).

$$RP_p = [\Delta P_p + (G_{pp} / B_{pp})\, \Delta Q_p] / V_p^2 \quad \text{-for PQ-nodes} \quad (39)$$

$$RQ_p = [\Delta Q_p - (G_{pp} / B_{pp})\, \Delta P_p] / V_p \quad \text{-for PQ-nodes} \quad (40)$$

$$RP_p = \Delta P_p / (K_p V_p^2) \quad \text{-for PV-nodes} \quad (41)$$

$$Y\theta_{pq} = \begin{cases} -1.0/X_{pq} & \text{-for all other branches} \\ -B_{pq} & \text{-for branches connected between two PV-nodes or a PV-node and the slack-node} \end{cases} \quad (42)$$

$$YV_{pq} = -1.0/X_{pq} \quad \text{-for all branches} \quad (43)$$

$$Y\theta_{pp} = \sum_{q>p} - Y\theta_{pq} \quad \text{and} \quad YV_{pp} = b_p' + \sum_{q>p} - YV_{pq} \quad (44)$$

$$b_p' = -2b_p \quad \text{or}$$
$$b_p' = -b_p + [QSH_p - (G_{pp} / B_{pp})\, PSH_p]/V_s^2 \quad \text{or}$$
$$b_p' = 2[QSH_p - (G_{pp} / B_{pp})\, PSH_p]/V_s^2 \quad (45)$$

where, K_p is defined in relation (29). This is the simplest method with very good performance for distribution networks in absence of PV-nodes (for systems containing only PQ-nodes). The large value of the difference [(1/X)-B], particularly for high R/X ratios branches connected to PV-nodes, creates modeling error when PV-nodes are present in a system.

Super Super Decoupled Loadflow: BX-version (SSDL-BX)

If super decoupling is applied only to QV-sub problem, the **SSDL-XX** method reduces to **SSDL-BX**, which makes it perform better for systems containing PV-nodes. The **SSDL-BX** method comprises relations (3) to (6), (46) to (48), (44) and (45). This method can be referred to as Advanced BX-Fast Decoupled Loadflow.

$$RP_p = \Delta P_p / V_p^2 \quad \text{-for all nodes} \tag{46}$$

$$RQ_p = [\Delta Q_p - (G_{pp} / B_{pp})\, \Delta P_p] / V_p \quad \text{-for PQ-nodes} \tag{47}$$

$$Y\theta_{pq} = -B_{pq} \quad \text{and} \quad YV_{pq} = -1/X_{pq} \tag{48}$$

It should be noted that Amerongen's General-purpose Fast Decoupled Loadflow method of reference-5 has turned out to be an approximation of this method. The approximation involved is only in relation (47). However, numerical performance is found to be only slightly better but more reliable than that of the Amerongen's method.

Super Super Decoupled Loadflow: X'B'-version (SSDL-X'B')

$$RP_p = [\Delta P_p' + (G_{pp}'/B_{pp}')\, \Delta Q_p'] / V_p^2 \quad \text{-for PQ-nodes} \tag{49}$$

$$RQ_p = \Delta Q_p'/ V_p \quad \text{-for PQ-nodes} \tag{50}$$

$$RP_p = [\Delta P_p / (K_p * V_p^2)] \quad \text{-for PV-nodes} \tag{51}$$

$$Y\theta_{pq} = -1/X_{pq}' \quad \text{and} \quad YV_{pq} = -B_{pq}' \tag{52}$$

$$Y\theta_{pp} = \sum_{q \neq p} -Y\theta_{pq} \quad \text{and} \quad YV_{pp} = b_p' + \sum_{q \neq p} -YV_{pq} \tag{53}$$

Where, $b_p' = -2b_p \mathrm{Cos}\Phi_p$ or

$b_p' = -b_p \mathrm{Cos}\Phi_p + QSH_p'/ V_s^2$ or

$b_p' = 2QSH_p'/ V_s^2$ (54)

Where, $\Delta P_p'$, $\Delta Q_p'$, PSH_p', QSH_p', $\mathrm{Cos}\Phi_p$, $\mathrm{Sin}\Phi_p$, K_p are defined in (23)to(29).This method consists of relations (3) to (6), (49) to (54), and (23) to (29). Best performance of this method could be achieved by restricting Φ_p in (27) and (28) to less than or equal to -48°.

Super Super Decoupled Loadflow: YB'-version (SSDL-YB')

The relation (49) in SSDL-X'B' implies unrestricted Φ_p is applied and it can take values up to -90 degrees. Therefore, (49) can be modified to (55) with consequent modification of (52) into (56).

$$RP_p = [\Delta P_p * \text{Absolute}\,[B_{pp} / v\,(G_{pp}^2 + B_{pp}^2)] + \Delta Q_p * [-\text{Absolute}\,[B_{pp} / v\,(G_{pp}^2 + B_{pp}^2)]] / V_p^2 \quad \text{-for PQ-nodes} \qquad (55)$$

$$Y\theta_{pq} = -Y_{pq} \quad \text{and} \quad YV_{pq} = -B_{pq}' \qquad (56)$$

This method consists of relations (3) to (6), (55), (50), (51), (56), (53) and (54), and (23) to (29). Best performance of this method could be achieved by restricting Φ_p in (27) and (28) to less than or equal to -48 degrees. Where, $\Delta P_p'$, $\Delta Q_p'$, PSH_p' , QSH_p' , $Cos\Phi_p$, $Sin\Phi_p$, K_p are defined in (23) to (29).

Super Super Decoupled Loadflow: B'X'-version (SSDL-B'X')

$$RP_p = \Delta P_p' / V_p^2 \quad \text{-for PQ-nodes} \qquad (57)$$

$$RQ_p = [\Delta Q_p' - (G_{pp}' / B_{pp}')\,\Delta P_p'] / V_p \quad \text{-for PQ-nodes} \qquad (58)$$

$$RP_p = [\Delta P_p / (K_p * V_p^2)] \quad \text{-for PV-nodes} \qquad (59)$$

$$Y\theta_{pq} = -B_{pq}' \quad \text{and} \quad YV_{pq} = -1/X_{pq}' \qquad (60)$$

$$Y\theta_{pp} = \sum_{q \neq p} -Y\theta_{pq} \quad \text{and} \quad YV_{pp} = b_p' + \sum_{q \neq p} -YV_{pq} \qquad (61)$$

Where, $b_p' = -2b_pCos\Phi_p$ or

$b_p' = -b_pCos\Phi_p + [QSH_p' - (G_{pp}' / B_{pp}')\,PSH_p']/V_s^2$ or

$b_p' = 2[QSH_p' - (G_{pp}' / B_{pp}')\,PSH_p']/V_s^2$ (62)

Where, $\Delta P_p'$, $\Delta Q_p'$, PSH_p', QSH_p', $Cos\Phi_p$, $Sin\Phi_p$, K_p are defined in (23)to (29).This method consists of relations (3) to (6), (57) to (62), and (23) to (29). Best performance of this method could be achieved by restricting Φ_p in (27) and (28) to less than equal to -48°.

Super Super Decoupled Loadflow: B'Y-version (SSDL- B'Y)

The realtion (58) in SSDL-B'X' implies unrestricted Φ_p is applied and it can take values up to -90 degrees. Therefore, (58) can be modified to (63) with consequent modification of (60) into (64).

$$RQ_p = [\Delta Q_p * Absolute [B_{pp} / v (G_{pp}^2 + B_{pp}^2)] - \Delta P_p * [-Absolute [B_{pp} / v (G_{pp}^2 + B_{pp}^2)]] / V_p^2 \quad \text{-for PQ-nodes} \quad (63)$$

$$Y\theta_{pq} = -B_{pq}' \quad \text{and} \quad YV_{pq} = -Y_{pq} \quad (64)$$

This method consists of relations (3) to (6), (57), (63), (59), (64), (61) and (62), and (23) to (29). Best performance of this method could be achieved by restricting Φ_p in (27) and (28) to less than or equal to -48 degrees. Where, $\Delta P_p'$, $\Delta Q_p'$, PSH_p' , QSH_p' , $Cos\Phi_p$, $Sin\Phi_p$, K_p are defined in (23) to (29).

Simultaneous (1V, 1θ) Iteration Scheme

An ideal to be approached for the decoupled Loadflow methods is the constant matrix Loadflow of reference-6 referred in this document as BGGB-method. In an attempt to imitate it, a decoupled class of methods with simultaneous (1V, 1θ) iteration scheme depicted by sequence of relations (65) to (69) is invented. This scheme involves only one mismatch calculation in an iteration. The correction vector is calculated in two separate parts without intermediate updating. Each iteration involves one calculation of [RQ], [ΔV], and [RP], [Δθ] to update [V] and [θ].

$$[\Delta V] = [YV]^{-1} [RQ] \quad (65)$$

$$[RP] = [\Delta P/V] - [G][\Delta V] \quad (66)$$

$$[\Delta\theta] = [Y\theta]^{-1}[RP] \quad (67)$$

$$[\theta] = [\theta] + [\Delta\theta] \quad (68)$$

$$[V] = [V] + [\Delta V] \quad (69)$$

In this invented class, each method differs only in the definition of elements of [RQ] and [YV]. The accuracy of methods depends only on the accuracy of calculation of [ΔV]. The greater the angular spread of branches terminating at PQ-nodes, the greater the inaccuracy in the calculation of [ΔV].

Super Super Decoupled Loadflow: BGX'-version (SSDL-BGX')

Numerical performance could further be improved by organizing the solution in a simultaneous (1V, 1θ) iteration scheme represented by sequence of relations (65) to (69). The elements of [RP], [RQ], [Yθ] and [YV] are defined by (70) to (74).

$$RQ_p = [\Delta Q_p' - (G_{pp}' / B_{pp}')\,\Delta P_p'] / V_p \qquad \text{-for PQ-nodes} \quad (70)$$

$$RP_p = (\Delta P_p/V_p) - \sum_{q=1}^{m} G_{pq}\Delta V_q \qquad \text{-for all nodes} \quad (71)$$

$$Y\theta_{pq} = -B_{pq} \qquad \text{and} \qquad YV_{pq} = -1/X_{pq}' \quad (72)$$

$$Y\theta_{pp} = \sum_{q\neq p} -Y\theta_{pq} \qquad \text{and} \qquad YV_{pp} = b_p' + \sum_{q\neq p} -YV_{pq} \quad (73)$$

$$b_p' = -2b_p\cos\Phi_p \quad \text{or}$$
$$b_p' = -b_p\cos\Phi_p + [QSH_p' - (G_{pp}'/B_{pp}')\,PSH_p']/V_s^2 \quad \text{or}$$
$$b_p' = 2[QSH_p' - (G_{pp}'/B_{pp}')\,PSH_p']/V_s^2 \quad (74)$$

Where, $\Delta P_p'$, $\Delta Q_p'$, PSH_p' , QSH_p' , $Cos\Phi_p$, $Sin\Phi_p$ are defined in (23) to (28).The SSDL-BGX' method comprises relations (65) to (74), and (23) to (28). Best possible convergence could be achieved by restricting rotations (Φ_p) in the range (-10° to -20°) in relations (27) and (28). The method is embodied in algorithm-3 and in the flow-chart of Fig.3.

Super Super Decoupled Loadflow: BGY-version (SSDL-BGY)

If unrestricted rotation is applied and transformed susceptance is taken as admittance values and transformed conductance is assumed zero (reference-6), the SSDL-BGX' method reduces to SSDL-BGY as defined by relations (75) to (79).

$$RQ_p = \Delta Q_p'/V_p = (\Delta Q_p Cos\Phi_p - \Delta P_p Sin\Phi_p)/V_p \quad \text{-for PQ-nodes} \tag{75}$$

$$RP_p = (\Delta P_p/V_p) - \sum_{q=1}^{m} G_{pq}\Delta V_q \quad \text{-for all nodes} \tag{76}$$

$$Y\theta_{pq} = -B_{pq} \quad \text{and} \quad YV_{pq} = -Y_{pq} \tag{77}$$

$$Y\theta_{pp} = \sum_{q\neq p} -Y\theta_{pq} \quad \text{and} \quad YV_{pp} = b_p' + \sum_{q\neq p} -YV_{pq} \tag{78}$$

$$b_p' = -2b_p Cos\Phi_p \quad \text{or}$$
$$b_p' = -b_p Cos\Phi_p + (QSH_p Cos\Phi_p - PSH_p Sin\Phi_p)/V_s^2 \quad \text{or}$$
$$b_p' = 2(QSH_p Cos\Phi_p - PSH_p Sin\Phi_p)/V_s^2 \tag{79}$$

The SSDL-BGY method comprises relations (65) to (69), and (75) to (79). It is the special case of the SSDL-BGX' method.

Super Super Decoupled Loadflow: BGX-version (SSDL-BGX)

If no (zero) rotation is applied, the SSDL-BGX' method reduces to SSDL-BGX as defined by relations (80) to (84).

$$RQ_p = [\Delta Q_p - (G_{pp}/B_{pp})\Delta P_p] / V_p \quad \text{-for PQ-nodes} \tag{80}$$

$$RP_p = (\Delta P_p/V_p) - \sum_{q=1}^{m} G_{pq}\Delta V_q \quad \text{-for all nodes} \tag{81}$$

$$Y\theta_{pq} = -B_{pq} \quad \text{and} \quad YV_{pq} = -1/X_{pq} \tag{82}$$

$$Y\theta_{pp} = \sum_{q\neq p} -Y\theta_{pq} \quad \text{and} \quad YV_{pp} = b_p' + \sum_{q\neq p} -YV_{pq} \tag{83}$$

$$b_p' = -2b_pCos\Phi_p \quad \text{or}$$
$$b_p' = -b_pCos\Phi_p + [QSH_p - (G_{pp}/B_{pp})PSH_p]/V_s^2 \quad \text{or}$$
$$b_p' = 2[QSH_p - (G_{pp}/B_{pp})PSH_p]/V_s^2 \tag{84}$$

The SSDL-BGX method comprises relations (65) to (69), and (80) to (84). It is again the special case of the SSDL-BGX' method.

Computation steps of SSDL-BGX', SSDL-BGY and SSDL-BGX methods (Algorithm-3):

a. Read system data and assign an initial approximate solution. If better solution estimate is not available, set voltage magnitude and angle of all nodes equal to those of the slack-node. This is referred to as the **slack-start.**

b. Form nodal admittance matrix, and Initialize iteration count ITR = 0.

ccc. Compute Sine and Cosine of nodal rotation angles using relations (28) and (27), and store them. If they, respectively, are less than the Sine and Cosine of any angle set (say in the range -10 to -20 degrees), equate them, respectively, to those of the same angle in the range -10 to -20 degrees. In case of zero rotation, Sine and Cosine value vectors are not required to be stored.

ddd. Form (m+k) x (m+k) size matrices [Yθ] and [YV] of (1) and (2) respectively each in a compact storage exploiting sparsity

1) In case of SSDL-BGX'-method, the matrices are formed using relations (72), (73), and (74)

2) In case of SSDL-BGY-method, the matrices are formed using relations (77), (78), and (79)

3) In case of SSDL-BGX-method, the matrices are formed using relations (82), (83), and (84)

In [YV] matrix, replace diagonal elements corresponding to PV-nodes by very large value (say, 10.0**10). In case [YV] is of dimension (m x m), this is not required to be performed. Factorize [Yθ] and [YV] using the same ordering of nodes regardless of node-types and store them using the same indexing and addressing information. In case [YV] is of dimension (m x m), it is factorized using different ordering than that of [Yθ].

e. Compute residues ΔP (PQ- and PV-nodes) and ΔQ (at only PQ-nodes). If all are less than the tolerance (ε), proceed to step (m). Otherwise follow the next step.

fff. Compute the vector of modified residues [RQ] using (70) in case of SSDL-BGX' , using (75) in case of SSDL-BGY, and using (80) in case of SSDL-BGX method for only PQ-nodes. Solve (65) for [ΔV]. While solving equation (65), skip all the rows and columns corresponding to PV-nodes. Compute the vector of modified residues [RP] using (71) or (76) or (81). Solve (67) for [Δθ].

ggg. Update voltage angles using, [θ] = [θ] + [Δθ]. and update PQ-node voltage magnitudes using [V] = [V] + [ΔV].

hhh. Set voltage magnitudes of PV-nodes equal to the specified values, and Increment the iteration count ITR=ITR+1, and proceed to step (e).

m. Calculate line flows and output the desired results

Triple lettered steps are characteristic steps of algorithm-3. The SSDL-BGX', SSDL-BGY and SSDL-BGX methods differ only in steps-ccc and -ddd defining gain matrices, and step-fff for calculating [RP] and [RQ]. Fig.3 is the flow-chart embodiment of algorithm-3.

Super Super Decoupled Loadflow: X'G_{pv}X'-version (SSDL- X'G_{pv}X')

Numerical performance could also be improved by organizing the solution in a simultaneous (1V, 1θ) iteration scheme represented by sequence of relations (65) to (69).

The elements of [RP], [RQ], [Yθ] and [YV] for this method are defined by (85) to (91).

$$RP_p = \{[\Delta P_p' + (G_{pp}'/B_{pp}')\Delta Q_p']/V_p^2\} - (g_p'\Delta V_p) \quad \text{-for PQ-nodes} \qquad (85)$$

$$RQ_p = [\Delta Q_p' - (G_{pp}/B_{pp}')\Delta P_p']/V_p \quad \text{-for PQ-nodes} \qquad (86)$$

$$RP_p = [(\Delta P_p/V_p^2) - \sum_{q=1}^{m} G_{pq}\Delta V_q]/K_p \quad \text{-for PV-nodes} \qquad (87)$$

$$Y\theta_{pq} = -1/X_{pq}' \quad \text{and} \quad YV_{pq} = -1/X_{pq}' \qquad (88)$$

$$Y\theta_{pp} = \sum_{q\neq p} -Y\theta_{pq} \quad \text{and} \quad YV_{pp} = b_p' + \sum_{q>p} -YV_{pq} \qquad (89)$$

$$b_p' = -2b_p\text{Cos}\Phi_p \quad \text{or}$$
$$b_p' = -b_p\text{Cos}\Phi_p + [QSH_p' - (G_{pp}'/B_{pp}')PSH_p']/V_s^2 \quad \text{or}$$
$$b_p' = 2[QSH_p' - (G_{pp}'/B_{pp}')PSH_p']/V_s^2 \qquad (90)$$

$$g_p' = 2b_p\text{Sin}\Phi_p \quad \text{or}$$
$$g_p' = b_p\text{Sin}\Phi_p + [PSH_p' + (G_{pp}'/B_{pp}')QSH_p']/V_s^2 \quad \text{or}$$
$$g_p' = 2[PSH_p' + (G_{pp}'/B_{pp}')QSH_p']/V_s^2 \qquad (91)$$

Where, $\Delta P_p'$, $\Delta Q_p'$, PSH_p' , QSH_p' , $\text{Cos}\Phi_p$, $\text{Sin}\Phi_p$, K_p are defined in (23) to (29). Again, if unrestricted rotation is applied and transformed susceptance is taken as admittance values and transformed conductance is assumed zero (reference-6), the **SSDL-X'G_{pv}X'** method reduces to **SSDL-YG_{pv}Y**. If no (zero) rotation is applied, the **SSDL-X'G_{pv}X'** method reduces to **SSDL-XG_{pv}X**. The SSDL-X'G_{pv}X' method comprises relations (65) to (69), (85) to (91), and (23) to (29). It is embodied in algorithm-4 and in the flow-chart of Fig.4.

Computation steps of SSDL-X'G_{pv}X', SSDL-YG_{pv}Y and SSDL-XG_{pv}X methods (Algorithm-4):

a. Read system data and assign an initial approximate solution. If better solution estimate is not available, set voltage magnitude and angle of all nodes equal to those of the slack-node. This is referred to as the **slack-start.**

b. Form nodal admittance matrix, and Initialize iteration count ITR= 0.

ccc. Compute Sine and Cosine of nodal rotation angles using relations (28) and (27), store them. If they, respectively, are less than the Sine and Cosine of any angle set (say 0 to -90 degrees), equate them, respectively, to those of the same angle in the range 0 to -90 degrees. In case of zero rotation, Sine and Cosine vectors are not required to be stored.

dddd. Form (m+k) x (m+k) size matrices [Yθ] and [YV] of (1) and (2) respectively each in a compact storage exploiting sparsity using relations (88), (89), and (90).
In [YV] matrix, replace diagonal elements corresponding to PV-nodes by very large value (say, 10.0**10). In case [YV] is of dimension (m x m), this is not required to be performed. Factorize [Yθ] and [YV] using the same ordering of nodes regardless of node-types and **store them using the same indexing and addressing information.** In case [YV] is of dimension (m x m), it is factorized using different ordering than that of [Yθ].

e. Compute residues ΔP (PQ- and PV-nodes) and ΔQ (at only PQ-nodes). If all are less than the tolerance (ε), proceed to step (m). Otherwise follow the next step.

ffff. Compute [RQ] using (86) for only PQ-nodes. Solve (65) for [ΔV]. While solving equation (65), skip all the rows and columns corresponding to PV-nodes. Compute the vector of modified residues [RP] using relations (85), (87), and (29). Solve (67) for [Δθ].

ggg. Update voltage angles using, [θ] = [θ] + [Δθ]. and update PQ-node voltage magnitudes using [V] = [V] + [ΔV].

hhh. Set voltage magnitudes of PV-nodes equal to the specified values, and Increment the iteration count ITR=ITR+1, and proceed to step (e)

m. Calculate line flows and output the desired results

Four lettered steps are characteristic steps of algorithm-4. This method is useful particularly for distribution systems without PV-nodes. Fig.4 is the flow-chart embodiment of algorithm-4.

Common Statements Concerning all methods:

In all the prior art and invented models [Yθ] and [YV] are real, sparse, symmetrical and built only from network elements. Since they are constant, they need to be factorized once only at the start of the solution. Equations (1) and (2) are to be solved repeatedly by forward and backward substitutions.

[Yθ] and [YV] are of the same dimensions (m+k) x (m+k) when only a row/column of the slack-node is excluded and both are triangularized using the same ordering regardless of the node-types. For a row/column corresponding to a PV-node excluded in [YV], use a large diagonal to mask out the effects of the off-diagonal terms. When the node is switched to the PQ-type the row/column is reactivated by removing the large diagonal. This technique is especially useful in the treatment of PV-nodes in the matrix [YV].

It is invented to make this technique efficient while solving (5) or (65) for [ΔV] by skipping all PV-nodes and factor elements with indices corresponding to PV-nodes. In other words efficiency can be realized by skipping operations on rows/columns corresponding to PV-nodes in the forward-backward solution of (5) or (65). This has been implemented and time saving of about 4% of the total solution time (including input/output) could be realized in 14-14 iterations required to solve 118-node system with the uniform R-scale factor of 4 applied. **It should be noted that the same indexing and addressing information can be used for the storage of both matrices as they are of the same dimension and sparsity structure.**

ALGORITHMS using GLOBAL CORRECTIONS

The algorithms-1, -2, -3, and -4 in the above involve incremental (or local) corrections. All the above algorithms can be organized to produce corrections to the initial estimate

solution. It involves storage of the vectors of modified residues and replacing the relations (17), (18), (19) by (92), (93), (94) respectively, and (4) or (68) and (6) or (69) respectively by (95) and (96). Superscript '0' in relations (95) and (96) indicates the initial solution estimate.

$$RP_p^r = [(\Delta P_p^r)' + (G_{pp}'/B_{pp}')(\Delta Q_p^r)']/(V_p^r)^2 + RP_p^{(r-1)} \quad (92)$$

$$RQ_p^r = [(\Delta Q_p^r)' - (G_{pp}'/B_{pp}')(\Delta P_p^r)']/(V_p^r)^2 + RQ_p^{(r-1)} \quad (93)$$

$$RP_p^r = \Delta P_p^r / [K_p(V_p^r)^2] + RP_p^{(r-1)} \quad (94)$$

$$\theta_p^r = \theta_p^0 + \Delta\theta_p^r \quad (95)$$

$$V_p^r = V_p^0 + \Delta V_p^r \quad (96)$$

RECTANGULAR COORDINATE FORMULATIONS OF INVENTED LOADFLOW METHODS

This involves following changes in the equations describing the loadflow models formulated in polar coordinates.

(i) Replace θ and $\Delta\theta$ respectively by f and Δf in equations (1),(3), (4), (67), (68) and (95)

(ii) Replace V and ΔV respectively by e and Δe in equations (2), (5), (6), (65), (66), (69) and (96)

(iii) Replace V_p by e_p and V_s by e_s in equations (17) to (19), (22), (30), (31), (33), (34), (38) to (41), (45) to (47), (49) to (51), (54), (55), (57) to (59), (62), (63), (70), (71), (74) to (76), (79) to (81), (84) to (87), (90), (91). The subscript 's' indicates the slack-node variable.

(iv) After calculation of corrections to the imaginary part of complex voltage (Δf) of PV-nodes and updating the imaginary component (f) of PV-nodes, calculate real component by:

$$e_p = \sqrt{V_{sp}^2 - f_p^2} \quad (97)$$

APPENDIX

Transformation of Branch Admittance

The branch admittance transformation for symmetrical gain matrices of the methods described in the above is given by the following steps:

1. Compute: $\Phi_p = \arctan (G_{pp}/B_{pp})$ and

$$\Phi_q = \arctan (G_{qq}/B_{qq}) \quad (98)$$

2. Compute the average of rotations at the terminal nodes (p and q) of a branch:

$$\Phi_{av} = (\Phi_p + \Phi_q)/2 \quad (99)$$

3. Compare Φ_{av} with the Limiting Rotation Angle (LRA) and let Φ_{av} to be the smaller of the two:

$$\Phi_{av} = \text{minimum } (\Phi_{av}, \text{LRA}) \quad (100)$$

4. Compute transformed pq-th element of the admittance matrix:

$$G_{pq}' + jB_{pq}' = (\text{Cos } \Phi_{av} + j \text{ Sin } \Phi_{av}) (G_{pq} + jB_{pq}) \quad (101)$$

5. Note that the transformed branch reactance is:

$$X_{pq}' = B_{pq}'/(G_{pq}'^2 + B_{pq}'^2) \qquad \text{and similarly,} \qquad (102)$$

$$X_{pp}' = B_{pp}'/(G_p^2 + B_{pp}'^2) \qquad (103)$$

In the description above X_{pq}' is the transformed branch reactance defined by equation (103) and B_{pq}' is the corresponding transformed element of the susceptance matrix. G_{pp}' and B_{pp}' are diagonal elements obtained from (102).

SOME POSSIBLE SIMPLE VARIATIONS OF SSDL-METHODS

1. Simple obvious modifications are the use of V_p and V_p^2 interchangeably in all expressions of RP_p, and the use of 1.0 for V_s^2 in all expressions of b_p' involving the term V_s^2
2. b_p' can also take values without transformation of b_p and QSH_p
3. Explicit algorithmic steps are not given for many variants of SSDL-X'X' except SSDL-YY, They are obvious from their descriptions and are similar to those of SSDL-YY method

EXPLANATORY STATEMENTS

The system stores a representation of the reactive capability characteristic of each machine and these characteristics act as constraints on the reactive power, which can be calculated for each machine.

While the description above refers to particular embodiments of the present invention, it will be understood that many modifications may be made without departing from the spirit thereof. The accompanying claims are intended to cover such modifications as would fall within the true scope and spirit of the present invention.

The presently disclosed embodiments are therefore to be considered in all respect as illustrative and not restrictive, the scope of the invention being indicated by the appended claims in addition to the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

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2. US Patent Number: 5081591 dated January 14, 1992: "Optimizing Reactive Power Distribution in an Industrial Power Network"
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Other Publications

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CLAIMS

The present invention is applicable to systems to process Loadflow computation by means of modified real and reactive power residues, and gain matrices derived from the Jacobian matrix. The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A method of controlling security (over load, under/over voltage) in a power system, comprising the steps of:

obtaining on-line data of nodal injections, voltages and phases at main nodes, and open/close status of circuit breakers in the power system,

establishing initial specifications of controlled parameters (real and reactive power at PQ-nodes, real power and voltage magnitude at PV-nodes, and transformer turns ratios etc.),

performing Loadflow computation at said nodes of the power system by a Super Super Decoupled computation in any of the Super Super Decoupled Loadflow methods or any of their hybrid combination or simple variants employing corresponding gain matrices derived from a super decoupled Jacobian matrix for real power with respect to angle and a super decoupled Jacobian matrix for reactive power with respect to voltage, and involving triangular factorization of said gain matrices and computing of discrepancy of real power and reactive power from specified values through such nodes,

said computing including introducing variables representing quotients of the transformed discrepancies from specified values of real and reactive power flowing in through each node divided by voltage, or square of the voltage in case of transformed real power mismatches in methods employing (1θ, 1V) iteration scheme, on each node, and using such variables to calculate values of angle and voltage for said transformed discrepancies from specified values of real and reactive power flowing in through each node, by using triangular factorization of said gain matrices for real and reactive power,

initiating said Loadflow computation with guess solution of the same voltage magnitude and angle as those of the slack (reference) node referred to as slack start,

restricting nodal transformation angle to maximum -48 degrees, applied to complex power injection in computing said transformed discrepancies from specified values of real and reactive power flowing in through each node,

evaluating the computed Loadflow for security (over load, under/over voltage),

correcting one or more controlled parameters with said correction (amount of over load and/or under/over voltage) values and repeating the computing and evaluating steps until evaluating step finds a good power system (no over load, no under/over voltage), and

effecting a change in the voltages and phases at said nodes of the power system by actually implementing the finally obtained values of controlled parameters after evaluating step finds a good power system.

2. A method as defined in claim1 wherein said Super Super Decoupled methods, employing successive (1θ, 1V) iteration scheme, of Loadflow computation are characterized in modifying the transformed real power residue at a PQ-node and real power residue at a PV-node by dividing them by squared voltage magnitude multiplied by a factor determined as a ratio of a diagonal element of susceptance matrix to a diagonal element of corresponding said gain matrix derived from transformed Jacobian matrix for real power with respect to angle.

3. A method as defined in claim1 wherein said Super Super Decoupled methods, employing simultaneous (1V, 1θ) iteration scheme, of Loadflow computation are characterized in that they involve only one time calculation of real and reactive power residues in an iteration unlike two calculations in successive (1θ, 1V) iteration scheme, and thereby achieving consequent speed-up.

4. A simple system/method of controlling generator and transformer voltages of more elaborate method of security control defined in claim 1 can be realised in a

system for controlling generator and transformer voltages in an electrical power utility containing plurality of electromechanical rotating machines, transformers and electrical loads connected in a network, each machine having a reactive power characteristic and excitation element which is controllable for adjusting the reactive power generated or absorbed by the machine, and some of the transformers having controllable taps for adjusting terminal voltage, said system comprising:

means defining any of Super Super Decoupled models of the network for providing an indication of the quantity of reactive power to be supplied by generators including at a reference node in dependence on representations of selected network electrical parameters,

machine control means connected to the said excitation element of at least one of the rotating machines for controlling the operation of the excitation element of at least one machine to produce or absorb the amount of reactive power indicated by said model means with respect to the set of representations.

5. A system as defined in claim 4 wherein the network includes a plurality of nodes each connected to at least one of: a reference generator, a rotating machine; and an electrical load, and the model has one of the 3-forms and their variants of Super Super Decoupled matrices which receives representations of selected values of the real and reactive power flow from each machine and to each load, and the model is operative for producing calculated values for the reactive power quantity to be produced or absorbed by each machine.

6. A system as defined in claim 4 wherein the utility further has at least one transformer having an adjustable transformation ratio, and said means defining a model is further operative for producing a calculated value for the transformer transformation ratio.

7. A system as defined in claim 4 wherein said machine control means are connected to said excitation element of each machine for controlling the operation of the excitation element of each machine.

8. A system as defined in claim 4 wherein said transformation ratio control means are connected to said transformer tap changing element of each transformer for controlling the operation of the transformer tap changing element of each transformer.

9. A method for controlling generator and transformer voltages in an electrical power utility containing plurality of electromechanical rotating machines, transformers and electrical loads connected in a network, each machine having a reactive power characteristic and excitation element which is controllable for adjusting the reactive power generated or absorbed by the machine, and some of the transformers having controllable taps for adjusting terminal voltage, said method comprising:

creating any of said Super Super Decoupled models of the network for providing an indication of the quantity of reactive power to be supplied by the generators in dependence on representations of selected network electrical parameters,

controlling the operation of the excitation element of at least one machine to produce or absorb the amount of reactive power indicated by any of the said Super Super decoupled models with respect to the set of specified parameters.

10. A method as defined in claim 9 wherein said step of controlling is carried out to control the excitation element of each machine.

11. A method as defined in claim 9 wherein said step of controlling is carried out to control the tap-changing element of each transformer.

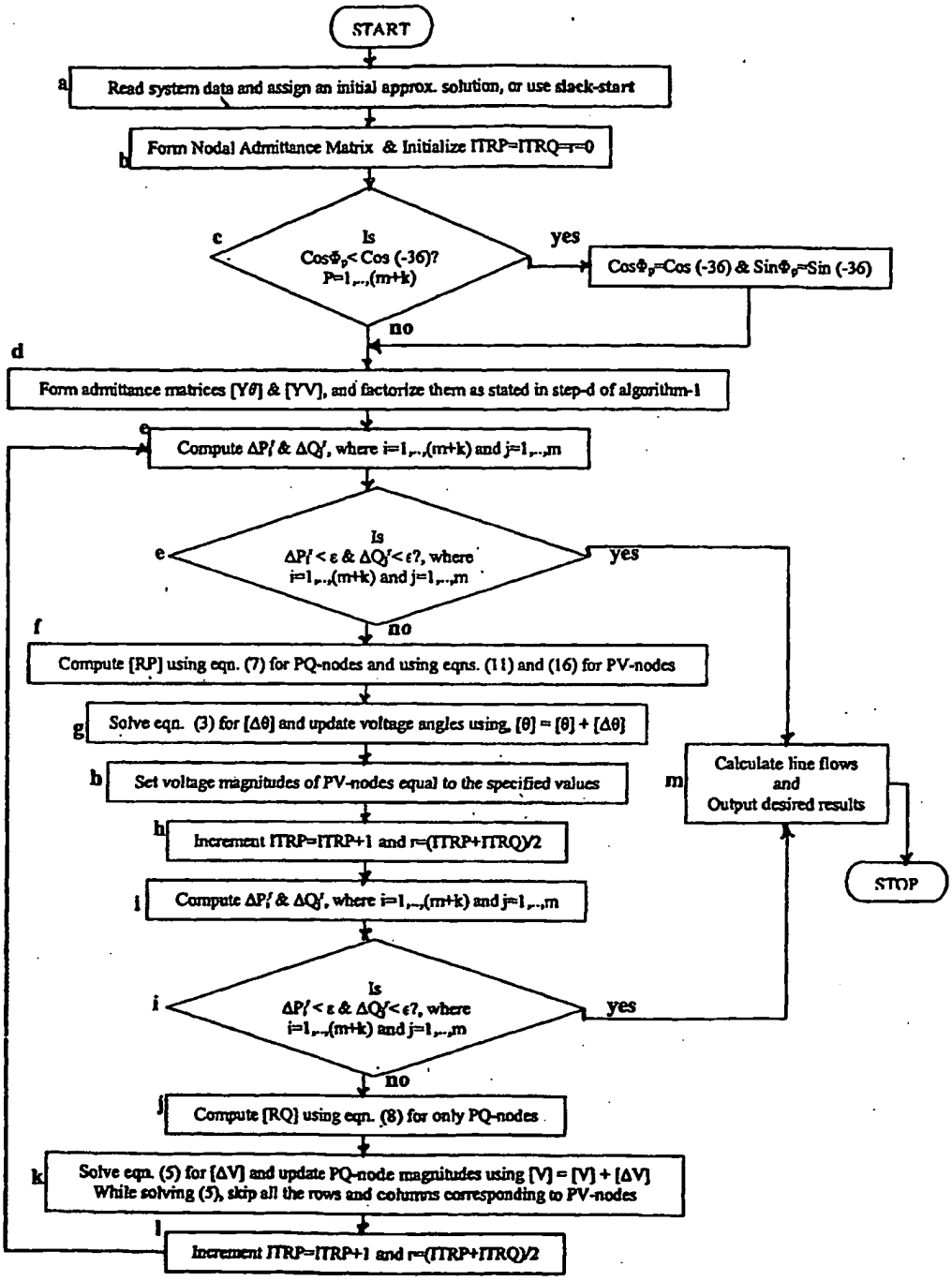

Fig.1: PRIOR ART: Flow-chart of FSDL solution algorithm-1

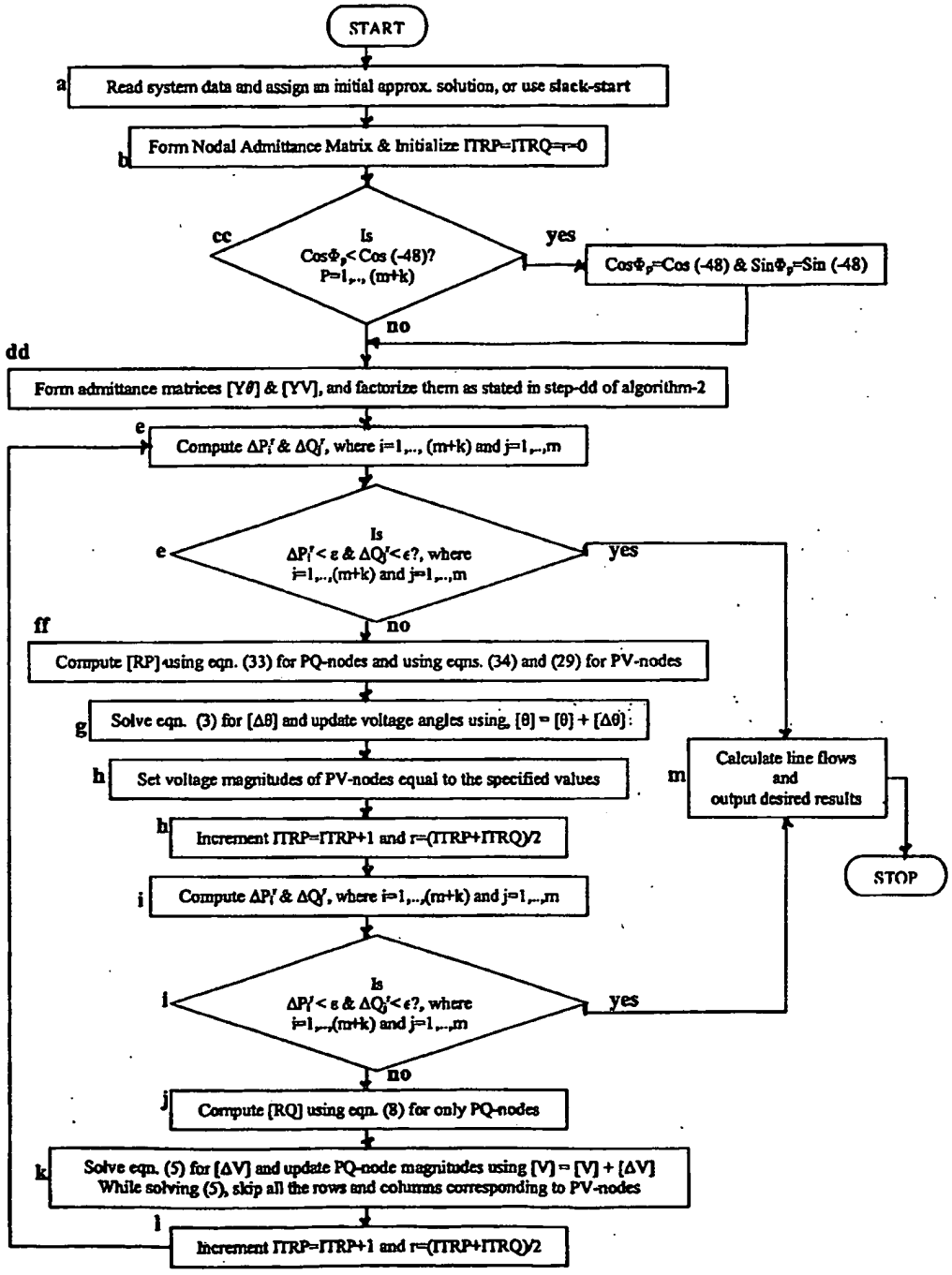

Fig.2: Invention: Flow-chart of SSDL-YY solution algorithm-2

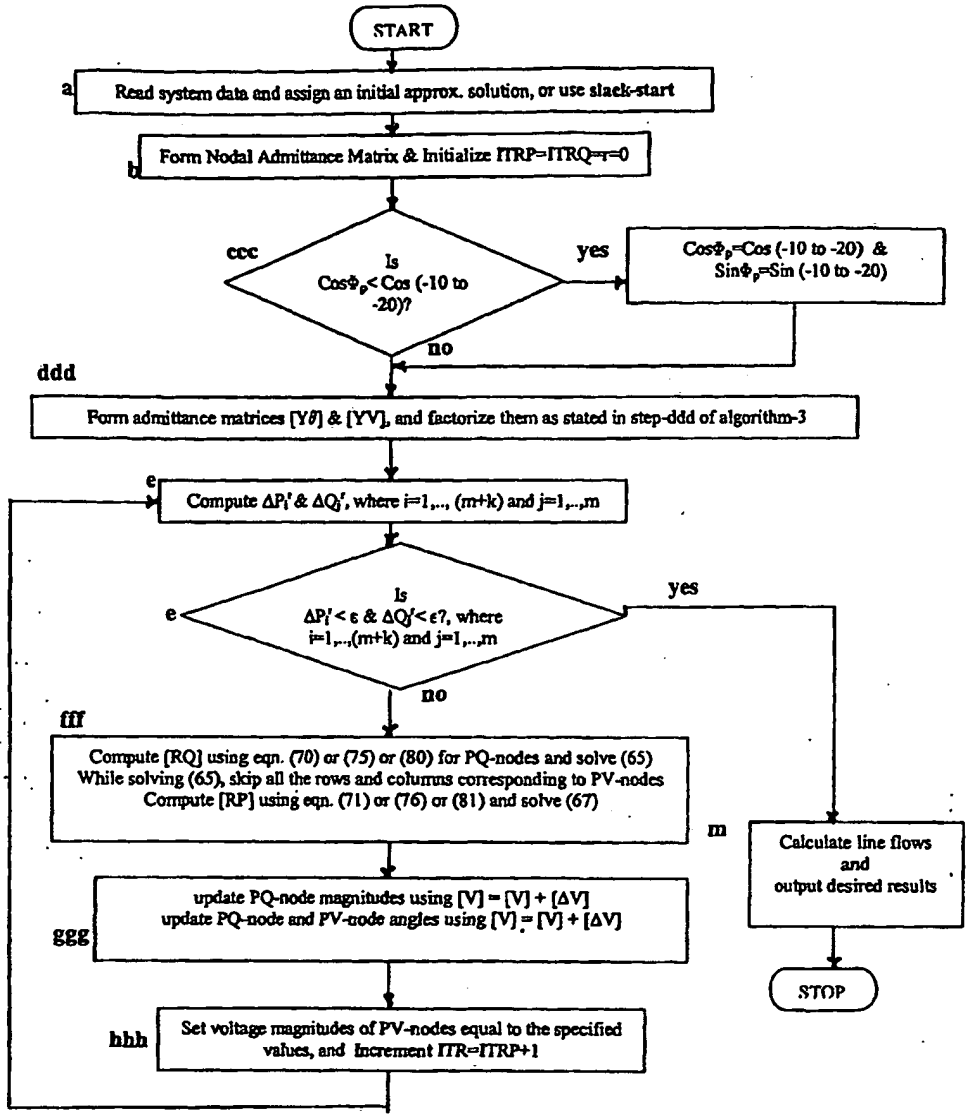

Fig.3: Invention: Flow-chart of SSDL-BGX' solution algorithm-3

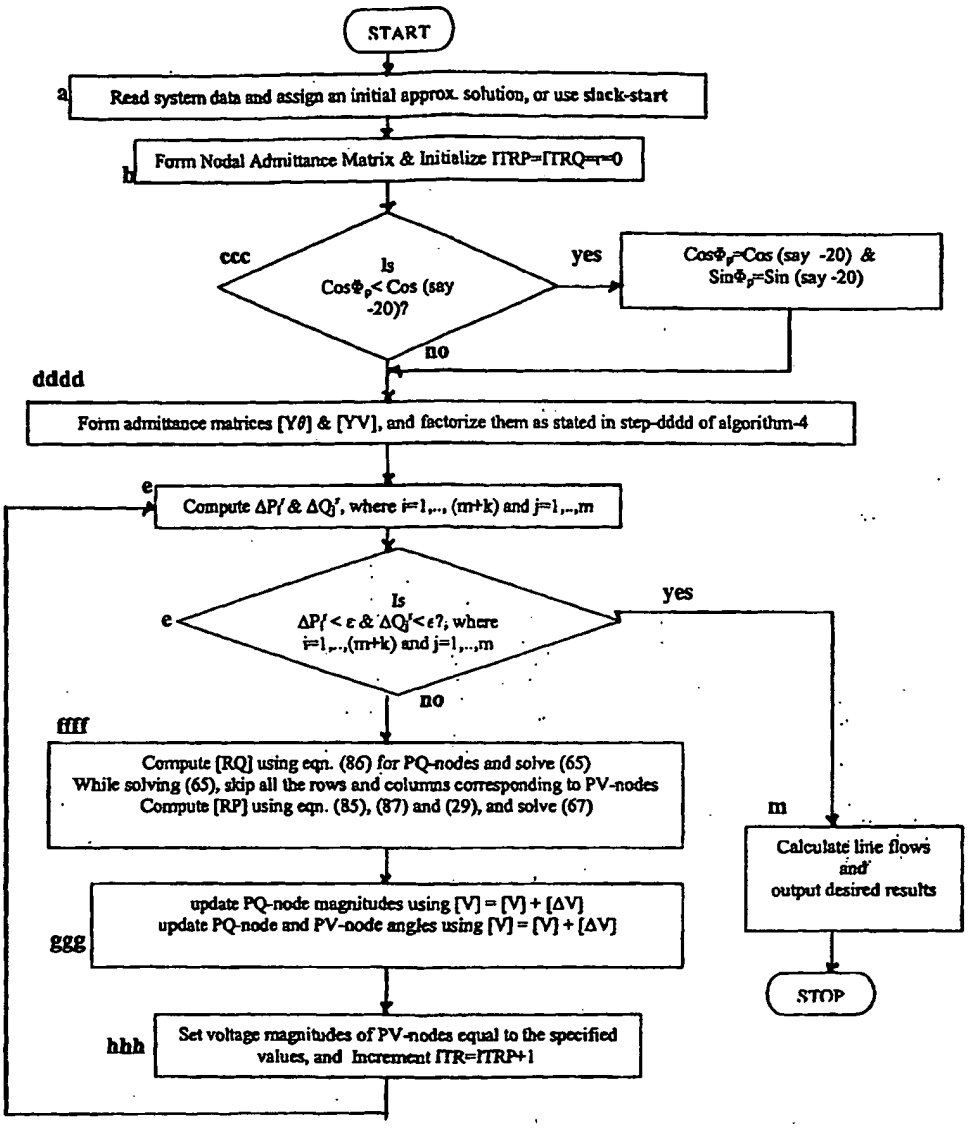

Fig.4: Invention: Flow-chart of SSDL-X'G_{pv}X' solution algorithm-4

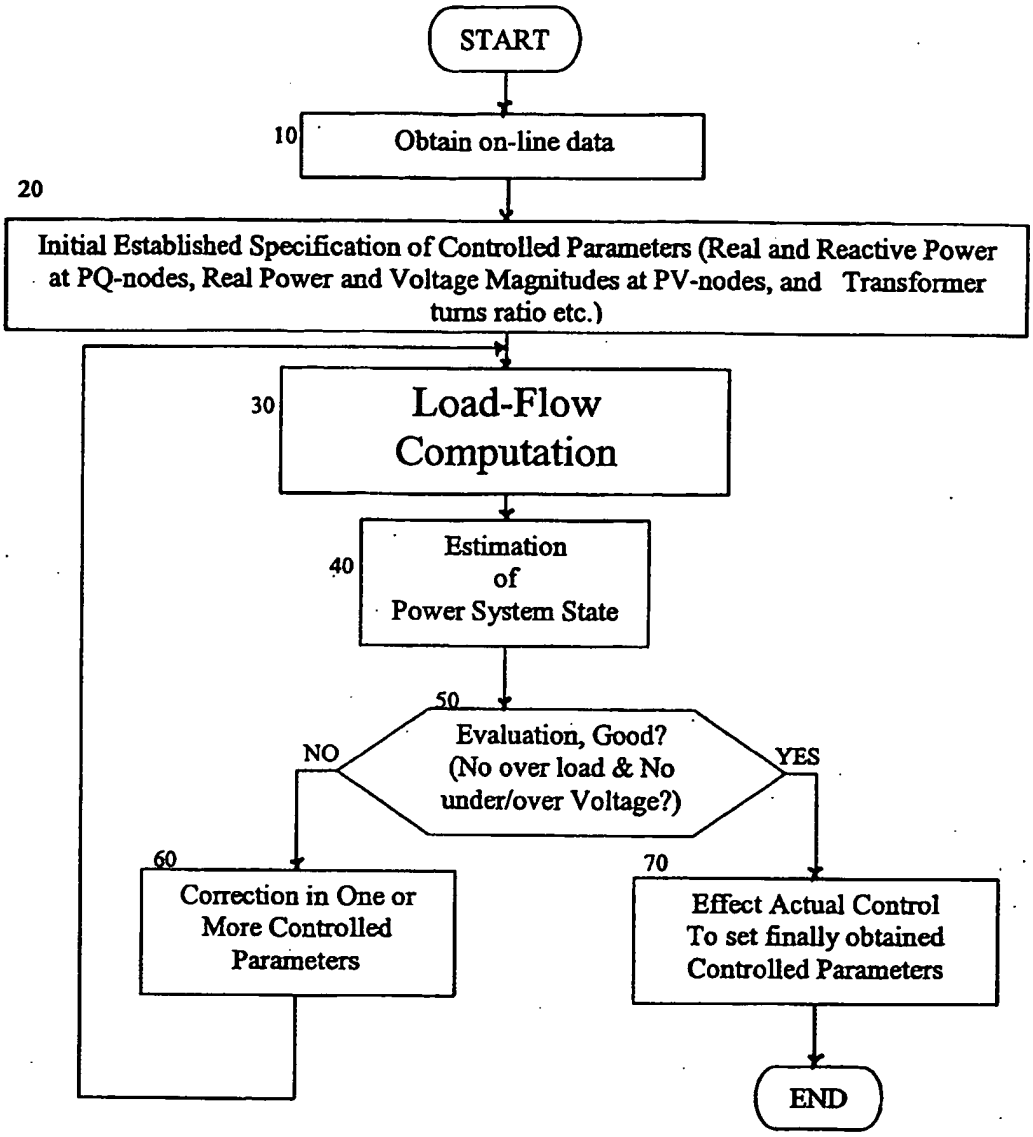

Fig. 5: **Load-Flow Computation in Security Control of Electrical Power System (PRIOR ART)**

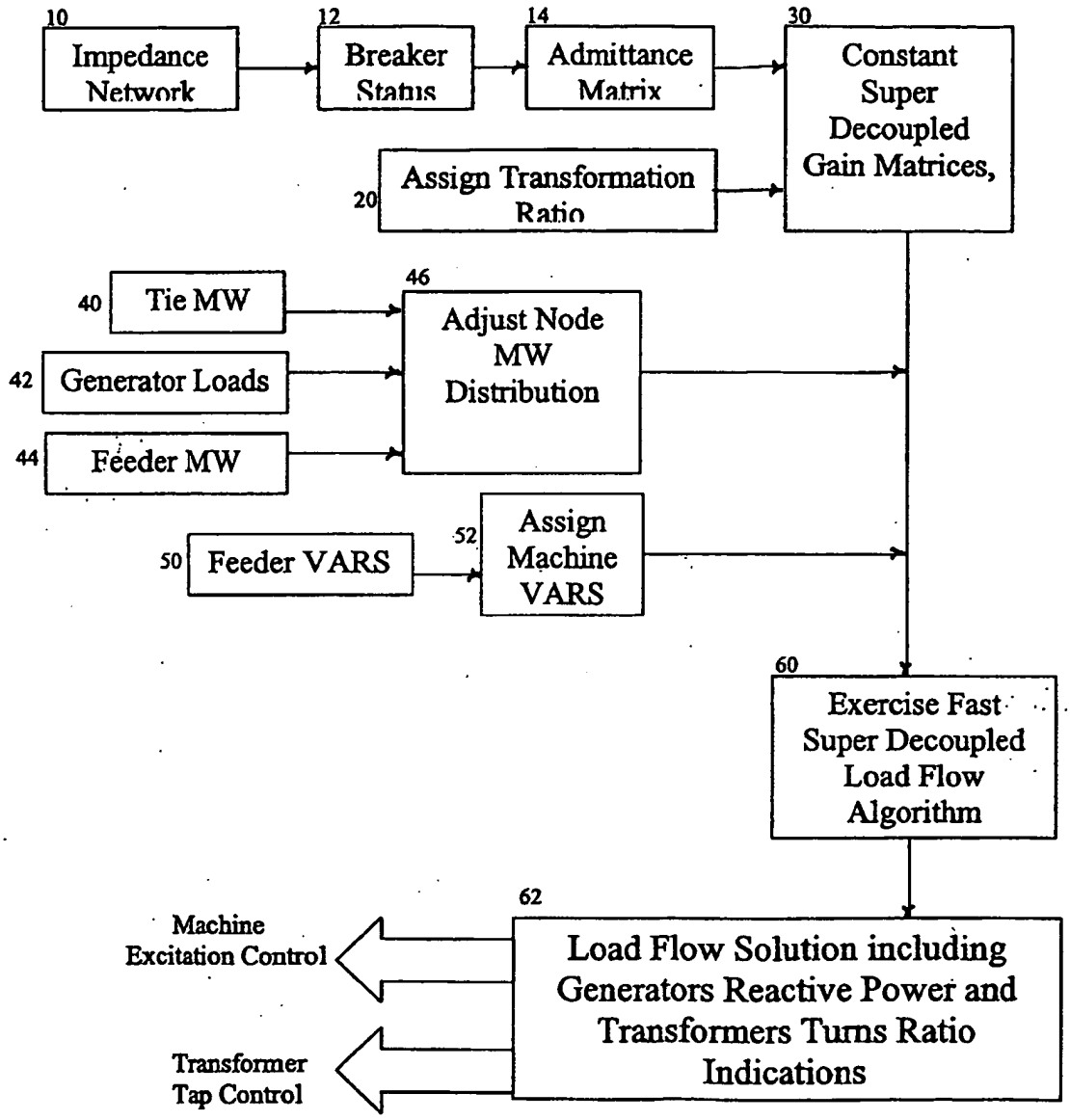

Fig. 6: **Load-Flow Computation in Voltage Control of Electrical Power System (PRIOR ART)**

DERWENT-ACC-NO: 2004-282949
DERWENT-WEEK: 200805
COPYRIGHT 2008 DERWENT INFORMATION LTD
TITLE: Security e.g. voltage controlling method for industrial power network, involves computing variables indicating quotients of discrepancies from values of real and reactive power in each node and evaluating load flow computation

INVENTOR: PATEL S; PATEL S B

PATENT-ASSIGNEE: PATEL S[PATEI] , PATEL S B[PATEI]

PRIORITY-DATA: 2002CA-2400580 (September 3, 2002)

PATENT-FAMILY:

PUB-NO	PUB-DATE	LANGUAGE
WO 2004023622 A2	March 18, 2004	EN
CA 2400580 A1	March 3, 2004	EN
AU 2003260221 A1	March 29, 2004	EN
AU 2003260221 A8	October 27, 2005	EN
EP 1661224 A2	May 31, 2006	EN
IN 200600436 P3	September 7, 2007	EN

DESIGNATED-STATES: AE AG AL AM AT AU AZ BA BB BG BR BY BZ CA CH CN CO CR CU CZ DE DK DM DZ EC EE ES FI GB GD GE GH GM HR HU ID IL IN IS JP KE KG KP KR KZ LC LK LR LS LT LU LV MA MD MG MK MN MW MX MZ NI NO NZ OM PG PH PL PT RO RU S C SD SE SG SK SL SY TJ TM TN TR TT TZ UA UG US UZ VC VN YU ZA ZM ZW AT BE BG CH CY CZ DE DK EA EE ES FI FR GB GH GM GR HU IE IT KE LS LU MC MW MZ NL OA PT RO SD SE SI SK SL SZ TR TZ UG ZM ZW AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IT LI LT LU L V MC MK NL PT RO SE SI SK TR

APPLICATION-DATA:

PUB-NO	APPL-DESCRIPTOR	APPL-NO	APPL-DATE
WO2004023622A2	N/A	2003WO-CA01312	August 29, 2003
CA 2400580A1	N/A	2002CA-2400580	September 3, 2002
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AU2003260221A8	N/A	2003AU-260221	August 29, 2003
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EP 1661224A2	N/A	2003WO-CA01312	August 29, 2003
IN 200600436P3	N/A	2003WO-CA01312	August 29, 2003
IN 200600436P3	Based on	2006IN-MN00436	March 28, 2006

INT-CL-CURRENT:

TYPE	IPC DATE
CIPP	H02J3/06 19680901
CIPS	H02J3/06 20060101

ABSTRACTED-PUB-NO: WO 2004023622 A2

BASIC-ABSTRACT:

NOVELTY - The method involves computing variables indicating quotients of discrepancies from specified values of real and reactive power of each node. Load flow computation is evaluated and controlled parameters are corrected with correction values e.g. over load. The computing and evaluating steps are repeated again to effect a change in voltage and phases at node of a power system, when evaluating step finds a good power system.

DESCRIPTION - INDEPENDENT CLAIMS are also included for the following:

(a) a system of controlling generator and transformer voltages

(b) a method of controlling generator and transformer voltages.

USE - Used for controlling security in a utility/industrial power network.

ADVANTAGE - The method facilitates to perform load flow computation in real-time operation, thereby effectively providing security against overload and under load voltage for a power system.

DESCRIPTION OF DRAWING(S) - The drawing shows a flow chart of a super decoupled load flow computation method.

CHOSEN-DRAWING: Dwg.2/6

TITLE-TERMS: SECURE VOLTAGE CONTROL METHOD INDUSTRIAL POWER NETWORK COMPUTATION VARIABLE INDICATE QUOTIENT DISCREPANCY VALUE REAL REACT NODE EVALUATE LOAD FLOW

DERWENT-CLASS: T01 T06 X12 X13

EPI-CODES: T01-J07; T06-A06A; X12-C02B; X12-H01A1; X12-H01B; X12-H03; X13-G02X;

SECONDARY-ACC-NO:

Non-CPI Secondary Accession Numbers: 2004-224351